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Coulomb Crystallization in Dusty Plasmas

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Ionized gases laden with fine charged dust grains are loosely referred to as dusty plasmas. Recently, lattice structures of negatively charged strongly coupled dust grains, called Coulomb crystals, have been formed in several laboratory plasma experiments. This three year project conducted fundamental theoretical research on issues important for understanding the basic physics of Coulomb crystallization in dusty plasmas. Models of the intergrain forces were developed, including attractive induced dipole forces in addition to repulsive screened Coulomb forces, and applied to modeling experimental data. The properties of low frequency dust acoustic waves and instabilities in strongly coupled dusty plasmas were investigated. Novel schemes for forming Coulomb lattices of positively charged grains were developed, involving grains that are charged positively either by ultraviolet (UV)-induced photoemission in a high-pressure gas, or by thermionic emission under laser heating. The use of UV to reduce dust trapping in process plasmas was also explored, and studies began on the use of dust as an electron source resulting from photoemission or thermionic emission. In addition, various waves and instabilities in collisional dusty plasmas were investigated.

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COULOMB CRYSTALLIZATION IN DUSTY PLASMAS

Abstract

Ionized gases laden with fine charged dust grains are loosely referred to as dusty plasmas. Recently, lattice structures of negatively charged strongly coupled dust grains, called Coulomb crystals, have been formed in several laboratory plasma experiments. This three year project conducted fundamental theoretical research on issues important for understanding the basic physics of Coulomb crystallization in dusty plasmas. Models of the intergrain forces were developed, including attractive induced dipole forces in addition to repulsive screened Coulomb forces, and applied to modeling experimental data. The properties of low frequency dust acoustic waves and instabilities in strongly coupled dusty plasmas were investigated. Novel schemes for forming Coulomb lattices of positively charged grains were developed, involving grains that are charged positively either by ultraviolet (UV)-induced photoemission in a high-pressure gas, or by thermionic emission under laser heating. The use of UV to reduce dust trapping in process plasmas was also explored, and studies began on the use of dust as an electron source resulting from photoemission or thermionic emission. In addition, various waves and instabilities in collisional dusty plasmas were investigated.

Technical Summary: Coulomb Crystallization in Dusty Plasmas

I. INTRODUCTION

A dusty plasma can be loosely defined as an ionized gas with dispersed charged solid particulates. or dust grains, of of micron to sub-micron sizes. The physics of dusty plasmas in space environments, such as planetary atmospheres and rings, comets, and the interplanetary and interstellar medium, has been studied for some time (e.g. Goertz, 1989; Mendis and Rosenberg, 1994). Recently there has been much interest in the physics of dust in laboratory plasma processing devices used in the microelectronics industry, mainly because dust contamination can lead to defects in microelectronic circuits (e.g. Selwyn, 1993; Bouchele, 1993). Important new developments in laboratory dusty plasmas involve recent experiments demonstrating the formation of Coulomb lattices of negatively charged dust grains in a plasma, called Coulomb crystals or 'plasma crystals' (Thomas et al, 1994; Chu and I, 1994; Hayashi and Tachibana, 1994, Melzer et al, 1994, Mohideen et al 1998). Dust grains can be highly charged in a plasma (due to plasma current collection), and can form a Coulomb lattice when their intergrain Coulomb potential energy is sufficiently larger than their thermal energy (Ikezi, 1986). This condition can be expressed as

$$\Gamma_d = \frac{Z_d^2 e^2}{d T_d} exp\left(-\frac{d}{\lambda_D}\right) > \Gamma_{dc} \tag{1}$$

where Z_d is the dust charge state. d is the inter-grain spacing, T_d is the dust grain thermal energy, λ_D is the plasma Debye length, with the exponential factor taking into account screening of the dust charge by the background plasma, and Γ_{dc} is some critical value for crystallization which is $\sim$ 170 for a one- component plasma (Ikezi, 1986). The structure of these *macroscopic* crystals, which have dust particles sizes ranging from microns to tens of microns, and intergrain spacings ranging from hundreds of microns to a millimeter, can be observed visually using laser light scattering and video cameras. It is now recognized that this entirely new material, could be a valuable tool for studying physical processes in condensed matter, such as melting, annealing, and lattice defects (Morfill and Thomas, 1996). And importantly, these structures may lead to the development of new materials or new technological applications. For example, there may be interesting Bragg diffraction effects for electromagnetic waves with wavelengths of the order of the interparticle spacing.

This three year project conducted fundamental theoretical research on issues important for understanding the basic physics of Coulomb crystallization in dusty plasmas. This included: studies of the intergrain forces in collaboration with an experimental group at the University of California, Riverside (UCR); studies of low frequency dust acoustic wave behavior in the liquid phase of strongly coupled dusty plasmas; development of novel schemes for forming Coulomb lattices of positively charged grains; studies of spin-off applications of positive

grain charging; and studies of waves and instabilities in dusty plasmas with application to laboratory and space plasmas.

II. SUMMARY

II.1 Work accomplished

In this section, a technical summary of the significant work accomplished is given, with reference to our list of scientific publications resulting from the work done under this grant, which is given at the end of this subsection.

In order to understand how the intergrain forces affect the Coulomb crystal structure, we investigated the role of forces other than the repulsive Coulomb force between like-charged grains. In Coulomb crystal experiments the grains are confined in the sheaths of the electrode configurations. In the vertical direction the grains are levitated by the electrostatic force associated with the electric field in the sheath, while the Coulomb repulsion between the like-charged grains keeps the spacing between the layers. In the horizontal direction, the grains are also confined by the force associated with the horizontal component of the electric field in the sheath associated with the particular electrode configuration. We have been collaborating on theory with Professor U. Mohideen and Dr. H. U. Rahman at the University of California, Riverside (UCR) who have been conducting experimental investigations of Coulomb crystallization in dusty plasmas. Their experiment has investigated a new regime of dust Coulomb crystal, where the grain sizes are of the order of $\sim 50\ \mu$m (larger than those in previous Coulomb crystal experiments), and where there appears to be a strong inter-grain attractive coupling which leads to the formation of distinct grain columns along the plasma sheath electric field. We have theoretically investigated the role of attractive intergrain forces, specifically, the role of an attractive dipole-dipole interaction between dust grains which acquire an induced dipole moment in the electric field of the plasma sheath. Assuming the electric field levitates the dust grains, the ratio of the attractive dipole-dipole force to the repulsive Coulomb force scales strongly with grain size, and may be of the order of unity for grain sizes of order tens of microns. We developed a simple phenomenological model wherein the intergrain spacing results from a balance of the attractive dipole-dipole force and the repulsive monopole (screened Coulomb) that appears consistent with the observed features of the UCR experiment. A joint paper on this topic was published, Ref. 12.

In order to understand the behavior of very low frequency fluctuations in certain dusty plasma Coulomb crystal experiments, we theoretically investigated the properties of dust acoustic waves in strongly coupled dusty plasmas. We considered the liquid phase, where Γ_d (from eq. 1) is $\gtrsim 10$ but less than the the critical Γ_{dc} for crystallization. The strong spatial

correlation of the dust grains can affect the dispersion relation of dust acoustic waves, which are the natural acoustic modes of oscillation of the charged dust component in the gas phase. The plasma was modeled as a strongly coupled Yukawa system, where the negatively charged dust grains interact strongly with each other via a Yukawa (i.e. screened Coulomb) potential, with the screening provided by the background electrons and ions which are classical and weakly correlated. Techniques developed to study waves in strongly coupled plasmas were used to investigate the dust acoustic wave spectrum. It was found that strong dust coupling leads to several effects on the dispersion relation of dust acoustic modes: (1) reduction of the phase speed for long wavelengths $\lambda \gg \lambda_D$, (2) reduction of the effective dust plasma frequency for $\lambda \sim \lambda_D$, and (3) the onset of negative dispersion (that is, $\partial\omega/\partial k < 0$) for smaller wavelengths. Since laboratory dusty plasmas generally have relatively high neutral pressure, the effect of collisions with neutrals, which leads to wave damping, was also included. In comparing our results with available experimental measurements of the dispersion of dust acoustic waves in the strong coupling regime, we found that collisional damping could swamp strong coupling effects, and suggested experimental parameters where the effects of strong dust coupling could be discerned. A paper in this area was published, Ref. 11, and two papers are in press, Refs. 13, 20. In the latter paper, we also presented an analysis of an ion-dust streaming instability driven by ions flowing in the plasma sheath region where dust Coulomb crystals are confined. It has been conjectured that such instability may be related to melting of the dust crystal. We had previously investigated such an instability in the dusty plasma-sheath regions of process plasmas, without taking into account the effect of strong coupling, and have published a paper on this topic, Ref. 5.

While most laboratory Coulomb crystal experiments have negatively charged grains, we developed theoretical schemes for forming novel Coulomb lattice of dust grains that are charged positively by either UV-induced photoemission in a high-pressure gas, or by thermionic emission under laser heating. It is well known theoretically that that dust grains can be charged positively by the photoelectric emission of electrons in the presence of a flux of ultraviolet (UV) photons with energy larger than the photoelectric work function of the grain. It is also known that dust grains can be charged positively by the thermionic emission of electrons, which occurs when the grain is heated sufficiently so that some electrons with energies near the Fermi level gain enough excess thermal energy to escape. If the dust grains are dispersed in a gas, the dust charge state produced by either of these processes depends on the interplay between the production process and the loss process(es) which in an inert gas is recombination onto the grains. This type of dust crystal, which has only two charged particle components (positively charged dust and electrons) may perhaps be a closer analog to ordinary metallic crystals than the 3-component (negatively charged dust, electrons, ions) Coulomb crystals. We found conditions for forming Coulomb crystals of dust grains with size of order microns to tens of microns in a high-pressure inert gas ($P > 1$ torr), under irradiation by a flux of UV photons (of intensity $\sim$ few W/cm^2) with energy larger than the work function of the grains, which can be as low as 2-3 eV for some metal oxides. We also considered methods for confining and levitating the dust using photophoretic forces, gas drag, and electrostatic forces. Two papers on this topic were published, Refs. 7,8. We also

found conditions for forming Coulomb crystals of ten micron-sized grains of work function $\sim$ 2.5 eV that are heated by a laser (intensity $\sim$ 400 W/cm^3) to a temperature of about 1700 K in a room temperature inert gas of pressure $\sim$ mbar. We have also outlined a possible experimental scheme for achieving such a crystal. This work has been accepted for publication, Ref. 19.

Related studies on positively charged grains included our theoretical suggestion on the use of UV to reduce particle trapping in process plasmas. The idea is that, if UV-induced photoemission could be used to lower the magnitude of the negative dust charge, the dust particles would be easier to remove from electrostatic traps in process plasmas, using various means. A paper was published on this topic, Ref. 9. Other related studies involved investigating the role of dust as an ionization source (a source of electrons) due to photoemission or thermionic emission in several terrestrial and space environments. For example, we showed that thermionic emission from very small (nm sized) soot particles could be the dominant source of ionization in sooting flames, and that thermionic emission from dust in the circumstellar shells around carbon-rich red giant stars could be one of the more dominant sources of ionization in those regions. A paper is in press on this topic, Ref. 23.

In addition, we investigated various waves and instabilities in dusty plasmas, and compared with available experimental results and observational data. We completed further studies on dust acoustic waves and instabilities in a dusty plasma in the gas phase, taking into account the effects of a dust size distribution as well as collisions with neutrals [Ref. 22], and we considered the nonlinear development of the instability in a collisional dusty plasma [Ref. 16]. In addition, we collaborated on a numerical study of dust acoustic waves in a strongly coupled dusty plasma [Ref. 24]. Further, since dusty plasma experimental devices are bounded, the effects of finite boundaries on the instability of ion flows to the excitation of dust acoustic waves was considered [Ref. 18]. We investigated other electrostatic instabilities in weakly correlated dusty plasmas. This included studies of the electrostatic ion cyclotron instability in dusty plasmas [Refs. 2,4] and in negative ion plasmas [Ref. 3], in which we found that the theory was consistent with available experimental results. We also considered an analogous instability associated with magnetized dust, the dust cyclotron instability, in a collisional dusty plasma [Refs. 17, 21]. We considered drift instabilities associated with dust and electron density gradients in a magnetized dusty plasma, where there is a localized spatial distribution of negative dust [Ref. 1]. The effect of dust on instabilities in the Earth's ionosphere was considered, including possible effects on an electrojet instability (the Farley-Buneman instability) in summer polar mesopause regions [Ref. 14], and instabilities related to the possible presence of charged dust (ice) in Space Shuttle exhaust experiments [Ref. 15]. Two reviews on waves and instabilities in dusty plasmas were published, Refs. 6,10.

The following is a list of the scientific publications, invited talks, and contributed talks and posters resulting from work done under this grant.

List of publications

1. Rosenberg, M. and Krall, N. A., "Low frequency drift instabilities in a dusty plasma," *Phys. Plasmas* **3**, 644 (1996).
2. Chow, V. W. and Rosenberg, M.," A note on the electrostatic ion cyclotron instability in dusty plasmas: comparison with experiment," *Planet. Space Sci.* **44**, 465 (1996).
3. Chow, V. W. and Rosenberg, M., "Electrostatic ion cyclotron instabilities in negative ion plasmas," *Phys. Plasmas* **3**, 1202 (1996).
4. Chow, V. W. and Rosenberg, M., "A comparison of the electrostatic ion cyclotron instability in dusty and negative ion plasmas," in *The Physics of Dusty Plasmas,* (ed., P. K. Shukla, D. A. Mendis, and V. W. Chow), World Scientific, Singapore, p. 141 (1996).
5. Rosenberg, M., "Ion-dust streaming instability in processing plasmas," *J. Vac. Sci. Technol. A* **14**, 631 (1996).
6. Rosenberg, M., "Instabilities in dusty plasmas," in *The Physics of Dusty Plasmas,* (ed., P. K. Shukla, D. A. Mendis, and V. W. Chow), World Scientific, Singapore, p. 129 (1996).
7. Rosenberg, M. and Mendis, D. A., "Plasma crystals with positively charged dust," in *The Physics of Dusty Plasmas,* (ed., P. K. Shukla, D. A. Mendis, and V. W. Chow), World Scientific, Singapore, p. 223 (1996).
8. Rosenberg, M., Mendis, D. A., and Sheehan, D. P., "UV-induced Coulomb crystallization of dust grains in high-pressure gas," *IEEE Trans. Plasma Sci.* **24**, 1422 (1996).
9. Rosenberg, M. and Mendis, D. A.,"Use of UV to reduce particle trapping in process plasmas," *IEEE Trans. Plasma Sci.* **24**, 1133 (1996).
10. Rosenberg, M., "Waves and instabilities in dusty plasmas", *Advances in Dusty Plasmas* (ed., P. K. Shukla, D. A. Mendis, and T. Desai), World Scientific, Singapore, p. 20 (1997).
11. Rosenberg, M., and Kalman, G., "Dust acoustic waves in strongly coupled dusty plasmas," Phys. Rev. E. **56**, 7166 (1997).
12. Mohideen, U., Rahman, H. U., Smith, M. A., Rosenberg, M., and Mendis, D. A., "Intergrain coupling in dusty plasma Coulomb crystals," *Phys. Rev. Lett.* **81**, 349 (1998).
13. Rosenberg, M., "Collective processes in strongly coupled dusty plasmas," to appear in *Strongly Coupled Coulomb Systems*, (ed. G. J. Kalman, K. B. Blagoev, and J. M. Rommel), Plenum Press, (1998).

14. Rosenberg, M., and Chow, V. W., "Farley-Buneman instability in a dusty plasma," *Planet. Space Sci.* **46**, 103 (1998).

15. Bharuthram, R., and Rosenberg, M., "A note on the generation of fluctuations by Space Shuttle exhaust in the ionosphere," *Planet. Space Sci.* **46**, 425 (1998).

16. Winske, D. and Rosenberg, M., "Nonlinear development of the dust acoustic instability in a collisional dusty plasma," *IEEE Trans. Plasma Sci.* **26**, 92 (1998).

17. Rosenberg, M., and Chow, V. W., " Collisional effects on the electrostatic dust cyclotron instability," *J. Plasma Phys*, accepted, (1998).

18. Rosenberg, M., and Shukla, P. K., "Instability of ion flows in bounded dusty plasma systems," *Phys. Plasmas*, in press, (1998).

19. Rosenberg, M., Mendis, D.A., and Sheehan, D.P., "Positively charged dust crystals induced by radiative heating," *IEEE Trans. Plasma Sci.*, accepted, 1998.

20. Rosenberg, M. and Kalman, G., " Effect of strong coupling on dust acoustic waves and instabilities," to appear in *Proc. 7th Workshop on the Physics of Dusty Plasmas*, (ed. M. Horanyi), AIP, 1998.

21. Chow, V. W. and Rosenberg, M., "A note on electrostatic ion/dust cyclotron instabilities in dusty plasmas," to appear in *Proc. 7th Workshop on the Physics of Dusty Plasmas*, (ed. M. Horanyi), AIP, 1998.

22. Iyer, L. and Rosenberg, M., "Effect of dust size distribution on a dust acoustic instability in a collisional plasma," to appear in *Proc. 7th Workshop on the Physics of Dusty Plasmas*, (ed. M. Horanyi), AIP, 1998.

23. Mendis, D. A., Rosenberg, M., and Chow, V. W., "Ionization equilibria in dusty plasma environments," to appear in *Proc. 7th Workshop on the Physics of Dusty Plasmas*, (ed. M. Horanyi), AIP, 1998.

24. Winske, D., Murillo, M., and Rosenberg, M., "Numerical simulation of dust-acoustic waves," *Phys. Rev. E*, submitted, 1998.

Invited talks

M. Rosenberg, "Waves and instabilities in dusty plasma", *3rd International Workshop on Interrelationship between Plasma Experiments in the Laboratory and in Space*, Pitlochry, Scotland, July 24-28, 1995.

D. A. Mendis, "Dusty plasmas," *3rd International Workshop on Interrelationship between Plasma Experiments in the Laboratory and in Space*, Pitlochry, Scotland, July 24-28, 1995.

M. Rosenberg, "Collective processes in dusty plasmas," *Dusty Plasmas - 95*, Wickenburg, Arizona, October 1-7, 1995.

D. A. Mendis, "Aspects of dust-plasma interactions," *Dusty Plasmas - 95*, Wickenburg, Arizona, October 1-7, 1995.

V. W. Chow, "Effects of grain size on charging processes," *Dusty Plasmas - 95*, Wickenburg, Arizona, October 1-7, 1995.

M. Rosenberg, "Waves and instabilities in dusty plasmas", *International Conference on the Physics of Dusty Plasmas*, Goa, India, October 21-25, 1996.

D. A. Mendis, "An historical overview of the progress in the physics of dusty plasmas," *International Conference on the Physics of Dusty Plasmas*, Goa, India, October 21-25, 1996.

V. W. Chow, D.A. Mendis, and M. Rosenberg, "The role of grain size in secondary and photoelectric emission from dust grains," *International Conference on the Physics of Dusty Plasmas*, Goa, India, October 21-25, 1996.

M. Rosenberg, "Collective processes in strongly coupled dusty plasmas," *International Conference on Strongly Coupled Coulomb Systems*, Boston College, Boston, MA, Aug. 3-10, 1997.

D. A. Mendis, "Dust in plasmas: from planetary rings to Coulomb crystals," *International Conference on Plasma Physics: New Perspectives of Collective Effects*, ICTP, Trieste, Italy, Nov. 10-14, 1997.

M. Rosenberg, "Dusty plasma as a new frontier," *URSI National Radio Science Meeting*, Univ. of Colorado, Boulder, CO, Jan. 5-8, 1998.

Contributed talks and posters

Rosenberg, M. and Kalman, G., "Dust acoustic modes in strongly coupled dusty plasmas," *1996 IEEE International Conference on Plasma Science: IEEE Conference record -abstracts*, p. 246, 1996.

Rosenberg, M. and Chow, V. W., "Low frequency cross-field instabilities in collisional dusty plasmas," *EOS* **77**, No. 46, p. F552, 1996.

Rosenberg, M., "Coulomb crystals with positively charged dust," talk, *10th International Conference on Superlattices, Microstructures, and Microdevices*, Lincoln, Neb., July 8-11, 1997.

Winske, D., Selwyn, G. S., and Rosenberg, M., "Low frequency waves in a dusty plasma crystal," *Bull. Am. Phys. Soc.* **42**, 1825, 1997.

Bharuthram, R., Singh, P., Rosenberg, M., and Chow, V. W., "Collisional effects on the electrostatic ion cyclotron instability in a dusty plasma," poster, *International Conference on Plasma Physics: New Perspectives of Collective Effects*, ICTP, Trieste, Italy, Nov. 10-14, 1997.

Rosenberg, M. and Kalman, G., "Dust acoustic waves and instabilities in strongly coupled dusty plasmas," talk, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

Mendis, D. A., Rosenberg, M., and Chow, V. W., "Ionization equilibria in dusty plasma environments," talk, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

Mohideen, U., Smith, M. A., Rahman, H. U., Rosenberg, M., and Mendis, D. A., " Intergrain coupling in dusty plasma Coulomb crystals," talk, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

Murillo, M. S. and Rosenberg, M., "Waves in dusty plasma crystals with dipole interactions," poster, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

Rosenberg, M., "Low frequency cross-field instabilities in collisional dusty plasmas," poster, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

Chow, V. W. and Rosenberg, M., "Collisional electrostatic dust cyclotron instability," poster, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

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Shukla, P.K. and Rosenberg, M., "Dust-acoustic holes and double layers via dust-vortex distributions," poster, *7th Workshop on the Physics of Dusty Plasmas*, Univ. of Colorado, Boulder, Co, Apr. 6-9, 1998.

Rosenberg, M., "Ionization in a dusty gas," poster, *1998 IEEE International Conference on Plasma Science: IEEE Conference record -abstracts*, p. 284, 1998.

II.2 Personnel

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